A Phase Diversity Sensor to Measure Piston Misalignment on the Keck II Segmented Mirror

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Outline

- Motivation (Relevance to Space Programs)
- Introduction to Phase Diversity
- Phase Diversity Sensor Design
- Experiment Layout (Drawings)
- Experiment Installation on Keck II
- Summary

Motivation

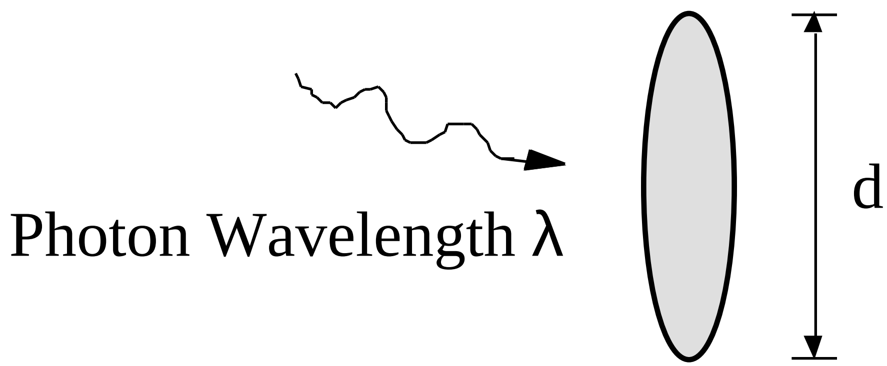
Scaling of a Mirror or Lens

Want to change:

$$\frac{\$\ \text{(Performance)}}{\$\ \text{(Cost, Size, Weight, Power)}}$$

Motivation

Scaling of a Mirror or Lens



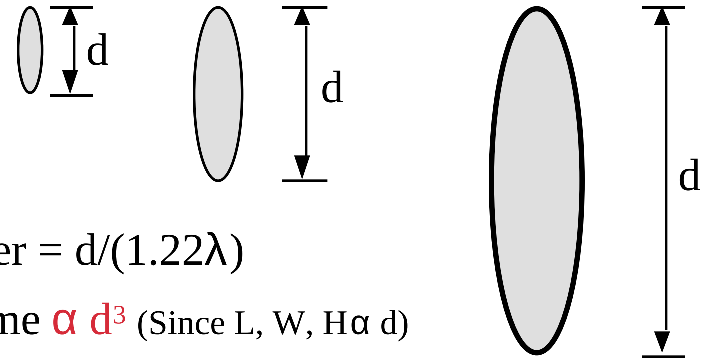
Performance – Resolving Power = d / (1.22 λ)

Cost – Size –Weight – (d) ^{3}

Motivation

Advantages of a Multiple Aperture or Sparse Aperture Mirror / Lens

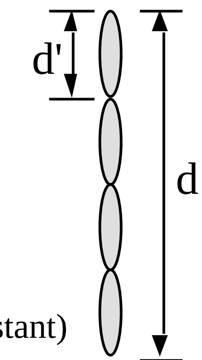
Simple Mirror or lens



Resolving Power = d/(1.22λ)

Weight α Volume α d^3 (Since L, W, H α d)

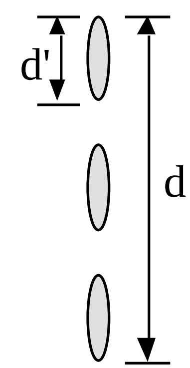
Multiple Aperture Advantage



Resolving Power Ú d/(1.22 λ)

Weight α Volume α d^2 (Since L, W α d; H = Constant)

Sparse Aperture Advantage



Resolving Power Ú d/(1.22 λ)

Weight α Volume < d^2 (Sparse Element Count)

Motivation

Problem:

How does one align a multiple or sparse aperture mirror in a telescope?

Solution:

1. Generate a reference beam to measure tilt and piston
    a. Artificial guide star with a Hartmann sensor
    b. Outgoing wave front interferometer

2. Use photons from viewed object
    a. Hartmann Sensor / Edge Sensors (Tilt / Piston)
    b. Shearing Interferometer
    c. Utilize an approach called Phase Diversity (PD)

Motivation

1. Generate a reference beam to measure tilt and piston
   - **a. Artificial guide star with a Hartman sensor**
   - **b. Outgoing wave front interferometer**

→ **A locally generated reference beam adds complexity, weight, and cost to an imaging system.**

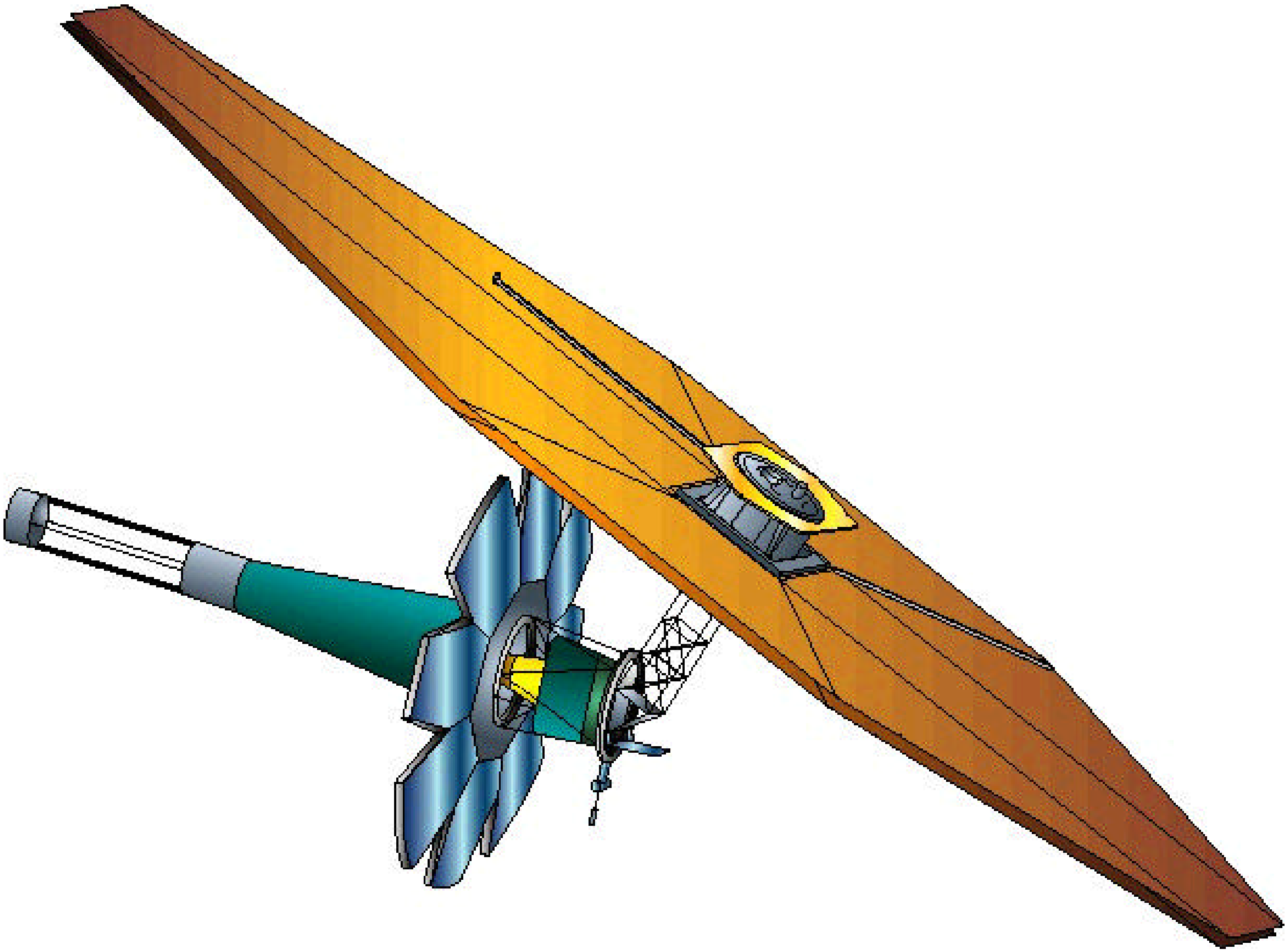
2. Use photons from viewed object
   - **a. Hartmann Sensor / Edge Sensors (Tilt / Piston)**
   - **b. Shearing Interferometer**

→ **Require reimaging optics which add complexity, weight, and cost.**

   - **c. Utilize a technique called Phase Diversity (PD)**

→ **System presented today**

Motivation



Many NGST design concepts rely on segmented primary mirrors (GSFC)

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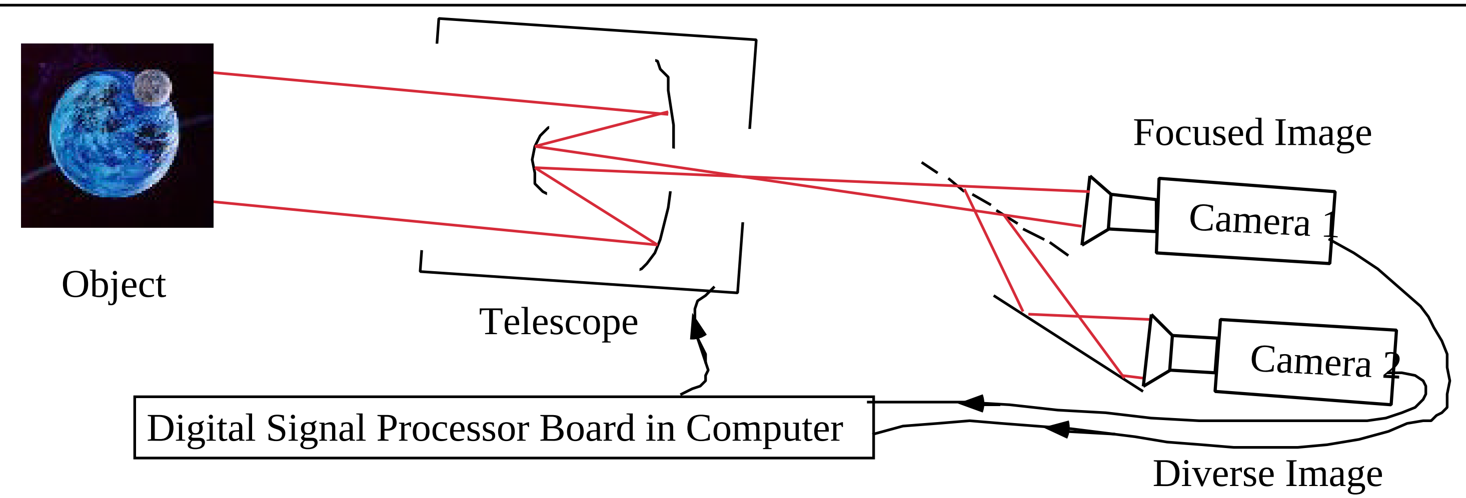
Introduction to Phase Diversity

Phase Diversity Technique:

a. Collect an in-focus image
b. Collect an out-of-focus (diverse) image

c. Utilize a phase diversity algorithm to measure the wavefront error.



Algorithm Design:

A variety of Phase Diversity algorithms are in use today

---> all are scene independent

a. ERIM - Paxman, Seldin, ...
b. Stockholm Observatory - Löfdahl, Sharmer
c. Lockheed Martin (GRNN) - Kendrick, Acton, Duncan, ...

Basic to all algorithms:

Let: $Q(f)$ = Fourier Transform of Object
$S_0(f)$ = Fourier Transform of Focused Image
$S_d(f)$ = Fourier Transform of Defocused Image
$H_0(f)$ = Optical Transfer Function (OTF) of Focused System
$H_d(f)$ = OTF of Defocused System

Introduction to Phase Diversity

Minimize a metric similar to the Golsalves metric.

$$E = \sum_f \frac{|S_0(f)\,\hat{H}_d(f) - S_d(f)\,\hat{H}_0(f)|^2}{|\hat{H}_0(f)|^2 + |\hat{H}_d(f)|^2}$$

(^) denotes the OTFs are working estimate

Generate Sharpness and Power Metrics
Solve using a General Regression Neural Network

$$\text{Sharpness Metric} = \frac{S_0(f)\,S_d^*(f) - S_0^*(f)\,S_d(f)}{S_0^*(f)\,S_0(f) + S_d^*(f)\,S_d(f)}$$

$$\text{Power Metric} = \frac{S_0(f)\,S_0^*(f) - S_d(f)\,S_d^*(f)}{S_0(f)\,S_0^*(f) + S_d(f)\,S_d^*(f)}$$

Introduction to Phase Diversity

GRNN: General Regression Neural Network

Solve for Y_0 given an N element training set.

$$Y_0 = \frac{\sum_{i=1}^{N} Y_i \exp(-R_i^2/\sigma^2)}{\sum_{i=1}^{N} \exp(-R_i^2/\sigma^2)}$$

where, $R_i^2 = (X_i - X_0)^T (X_i - X_0)$

R_i = Euclidean distance from X_0 to each of the X_i points.

σ - determines the width of influence of each data point.

(X_i, Y_i) is a training set pair: X_i = Metric, Y_i = Aperture Configuration

(X_0, Y_0): X_0 = Measured Metric, Y_0 = Calculated Configuration

--> <u>Detailed algorithm design is a topic of the next talk</u> <--

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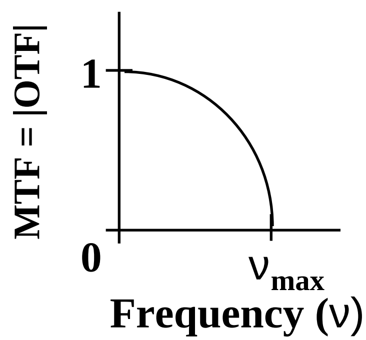
Phase Diversity Sensor Design

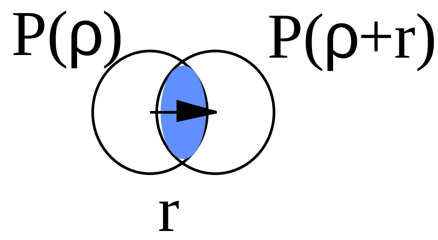
Design Issues:

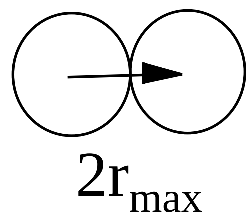
1. Critical Sampling on Camera Pixels (F# of system)
2. Amount of Defocus
3. Sensor Optics Layout
4. Optical Designs (Telecentric)
5. Acquisition Parameters:
    a. Filter Spectral Bandwidth (nm)
    b. Camera Shutter Speeds (ns)
    c. Neutral Density Filters
6. Environment (High Altitudes, Low Temperatures)

Critical Sampling of Images

Require camera to critically sample the images:







P(ρ) = Pupil Function

Math:

OTF = $H(\nu) = Ap(\lambda d_i \nu)$, where d_i = image dist. = f (for an object at ∞)

Now: MTF = 0 at $\nu = \nu_{max}$

$\Longrightarrow Ap(\lambda f\, \nu_{max}) = Ap(2r_{max}) = 0$; $\Longrightarrow \lambda f\, \nu_{max} = 2r_{max}$

Critical sampling: $\nu_{max} = 1/(2h_{max})$, h =pixel pitch (Nyquist Theorem)

Airy Disk Diameter = $2.44\, \lambda f/2r_{max} = 2.44\, \lambda f / (\lambda f\, \nu_{max}) = 4.88\, h_{max}$

===> Airy Disk Diameter = 4.88 * Pixel Pitch

Critical Sampling on Camera Pixels

Critical sampling occurs when the Airy disk diameter is sampled by 4.88 pixels

Set: 4.88 = Airy disk diameter / pixel pitch = $[2.44 * (F^{/\#}) * \lambda] / [h]$
where h is the pixel pitch

Given λ, h:
For critical sampling or better: $(F^{/\#}) > 2\, h / \lambda$

For the 900 nm sensor with 6.8 µm pixels: $(F^{/\#}) > 2\, h / \lambda = 15.1$
For the 1662 nm sensor with 50 µm pixels: $(F^{/\#}) > 2\, h / \lambda = 61.7$

Note: (If Define: $Q^{/\#} = (\lambda/D) * (f/h)$, then $Q^{/\#} = 2$ corresponds to critical sampling).

Phase Diversity Amount of Defocus

The amount of defocus at the two wavelengths is determined from:

1. Simulations
2. Empirical Data from Processing Images

For the two sensors described above:

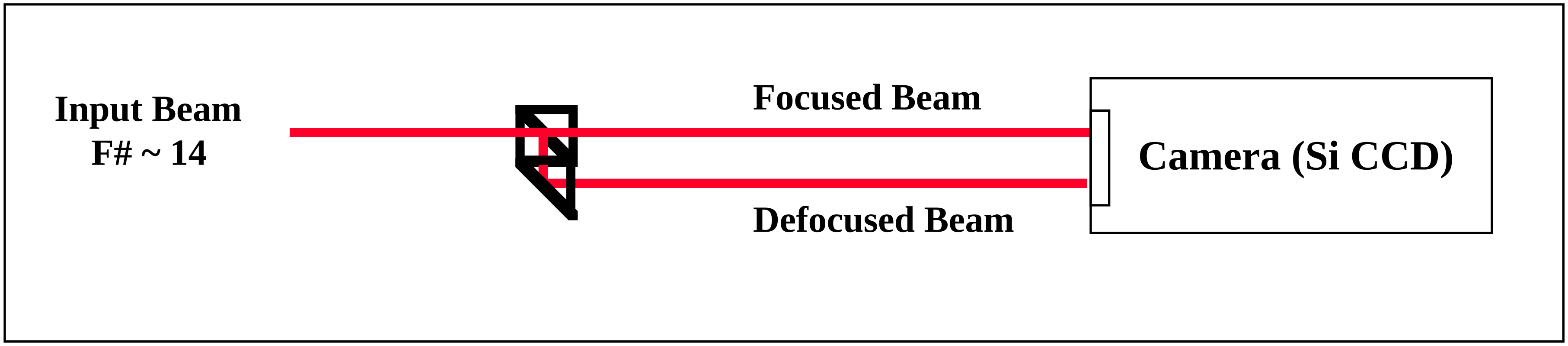
1. At 900 nm, 1.9 waves of defocus was used
2. At 1662 nm, 1.0 waves of defocus was used

Number of waves of defocus = ΔZ / [$8 \lambda (F^{/\#})^2$]

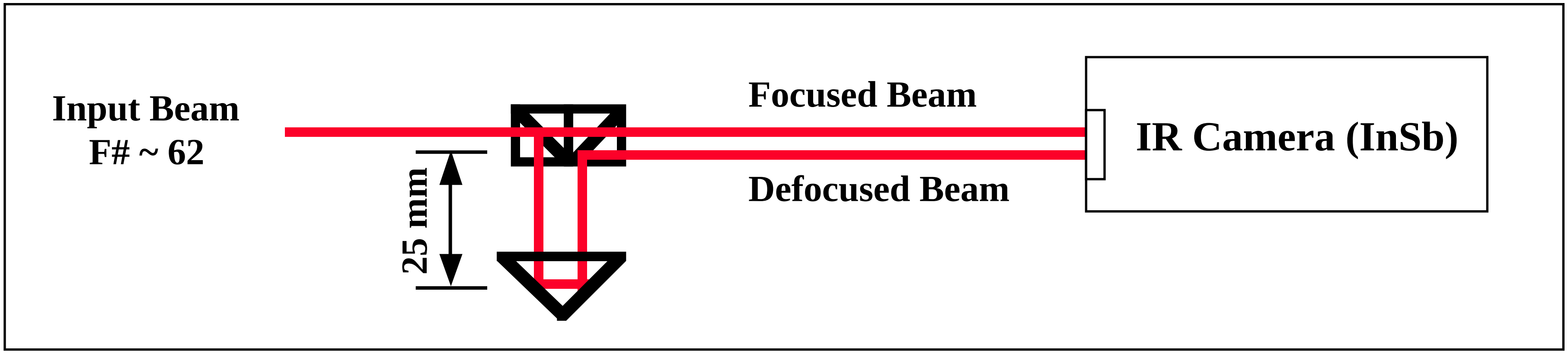
where, ΔZ = displacement along the optical axis

Phase Diversity Sensor Optics Layout

Phase Diversity Sensor 1: (F# = 15, Camera pixel pitch = 6.8 µm, λ = 900nm)

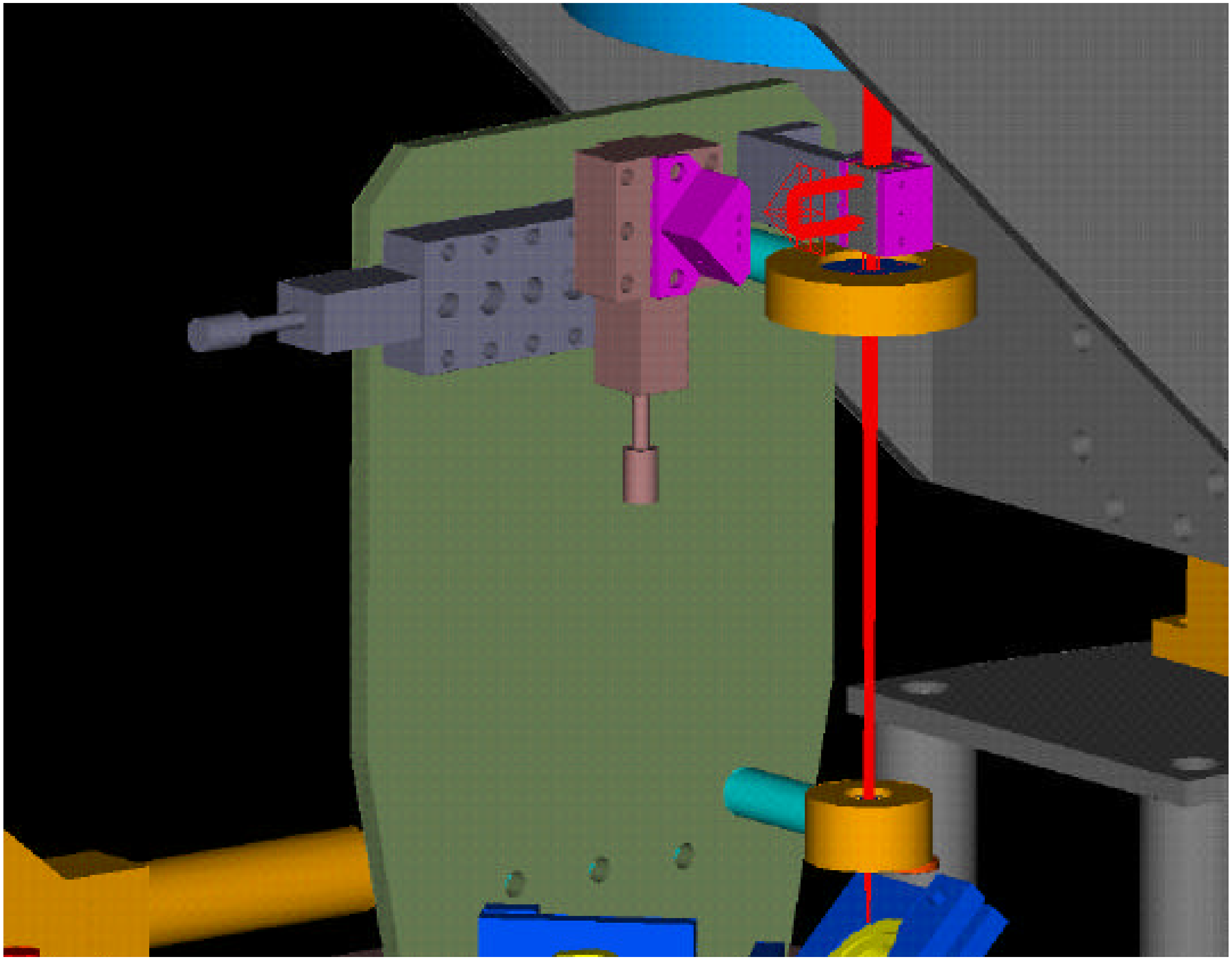


Proposed Phase Diversity Sensor 2: (F# = 62, Camera pixel = 50.0 µm, λ = 1662nm)



Only one camera is needed for each PD sensor; both beams projected onto same array.

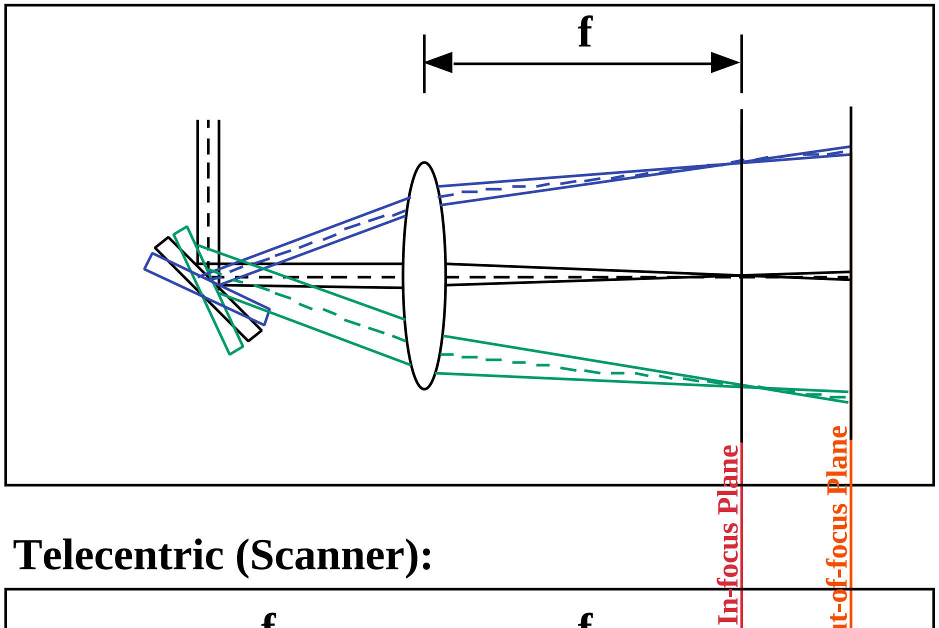
PD Sensor (1662 nm)



Side View

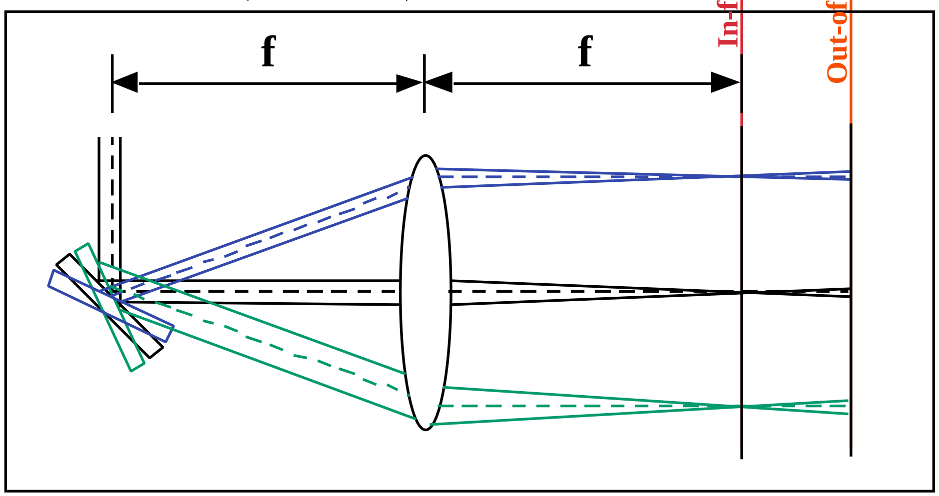
Optical Designs (Telecentric)

Normal (Scanner):



Size of in-focus image ≠ Size of out-of-focus image

Telecentric (Scanner):



Size of in-focus image = Size of out-of-focus image

A “Telecentric Stop” may also be used.

Acquisition Parameters

Filter Spectral Bandwidth (nm)

- filter bandwidth is 10 nm (at a pass wavelength of 900 nm)
- dispersion < 0.002 arcseconds when 20 degrees off the zenith
- this is less than 10 % of the diffraction spot size
- this results in about a 10 % elongation of the diffraction-limited PSF
- will view objects less than 20 degrees off the zenith

Camera Shutter Speeds (ns)

- Keck studies of speckle use 134 ms exposures at λ = 2.2 µm
- at λ = 900 nm this corresponds to about 55 ms exposures
- ==> use exposures less than 50 ms
- On Photometrics camera, the minimum exposure time is 14 ms

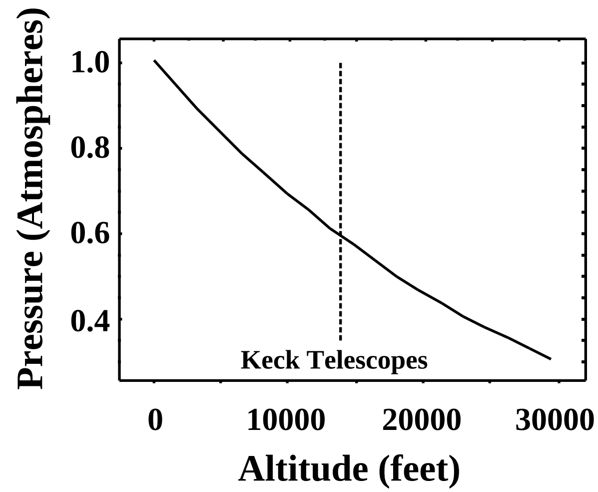
Neutral Density Filters

- use neutral density filter set to adjust exposure
- Fused Silica, Surface Flatness: 2λ per 25 mm
- Set contains: Nominal Densities of 0.03, 0.1, 0.3, 0.5, 1.0, 2.0, 3.0

Environmental Effects

High Altitude (13,780 feet)

- Most hard drives not rated above 10,000 feet
- Mountain Optech
  - High altitude magnetic hard drive
  - 2.0 GByte
  - Rated to 20,000 feet
- Pinnacle Micro: Magneto-Optical Drive
  - Vertex 2.3 GByte
  - Two sided cartridges
  - Store 1.15 GByte / Side
  - Rated to 20,000 feet



Low Ambient Temperatures (-5 °C)

- All equipment functioned at these temperatures

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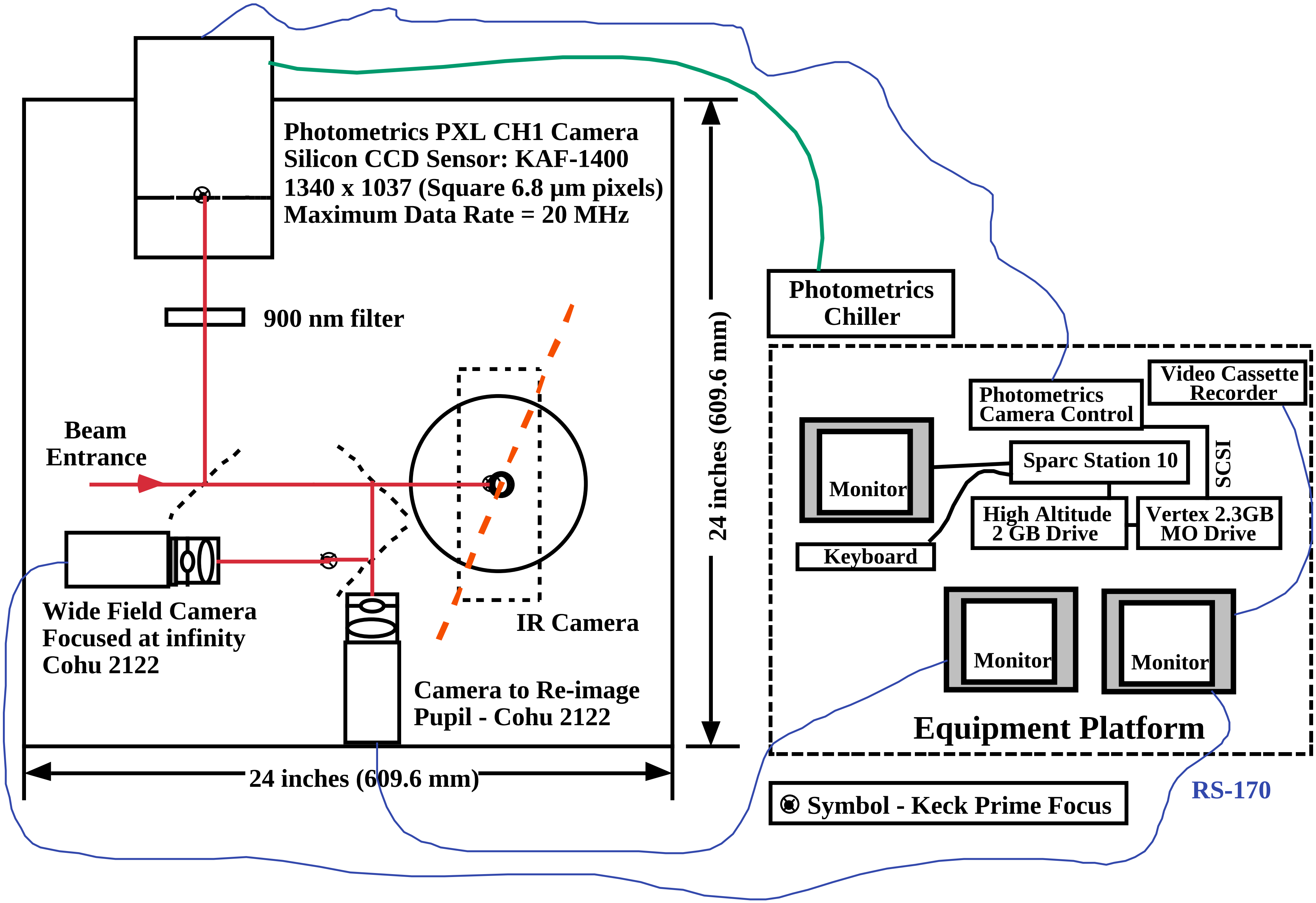
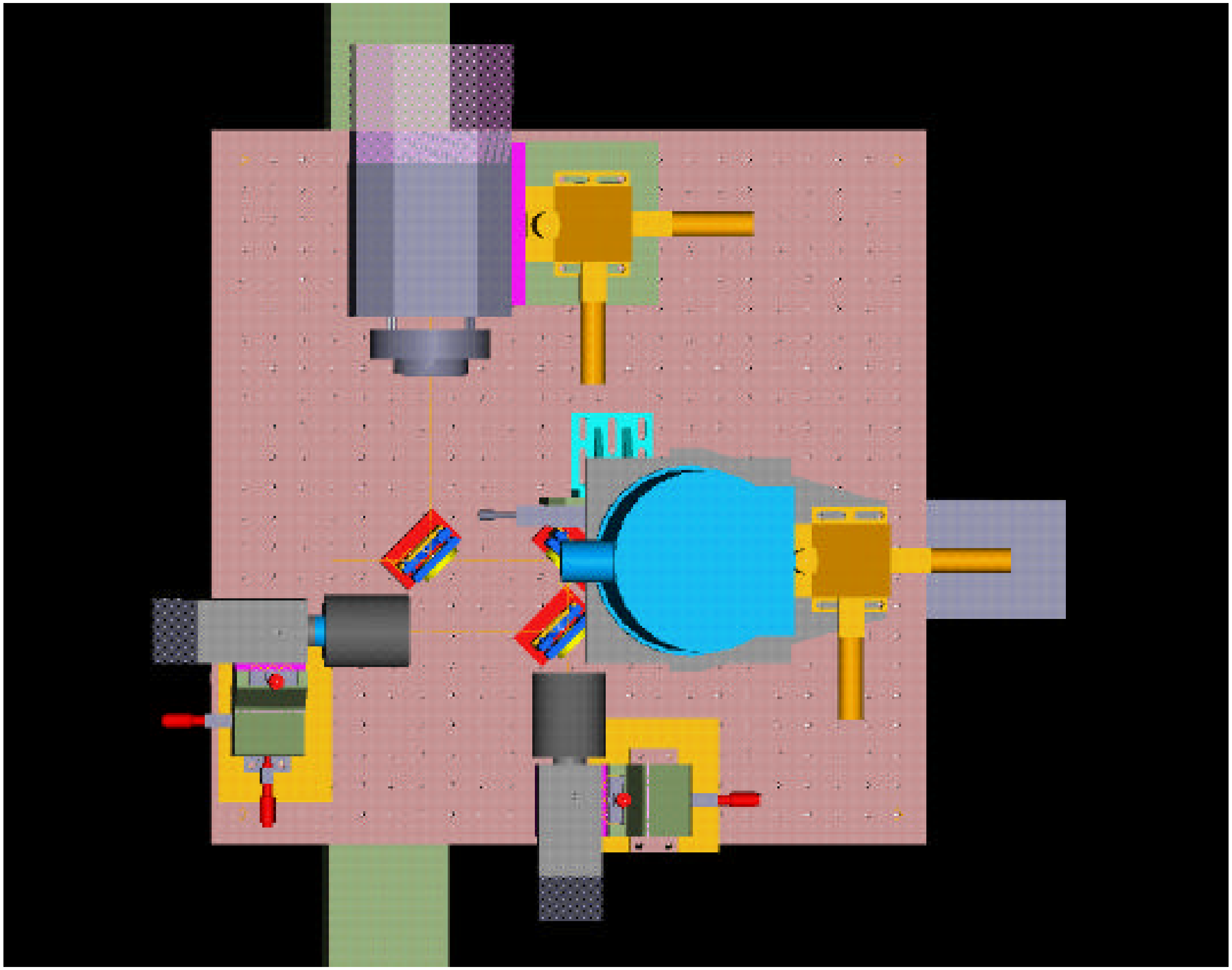
Experiment Schematic

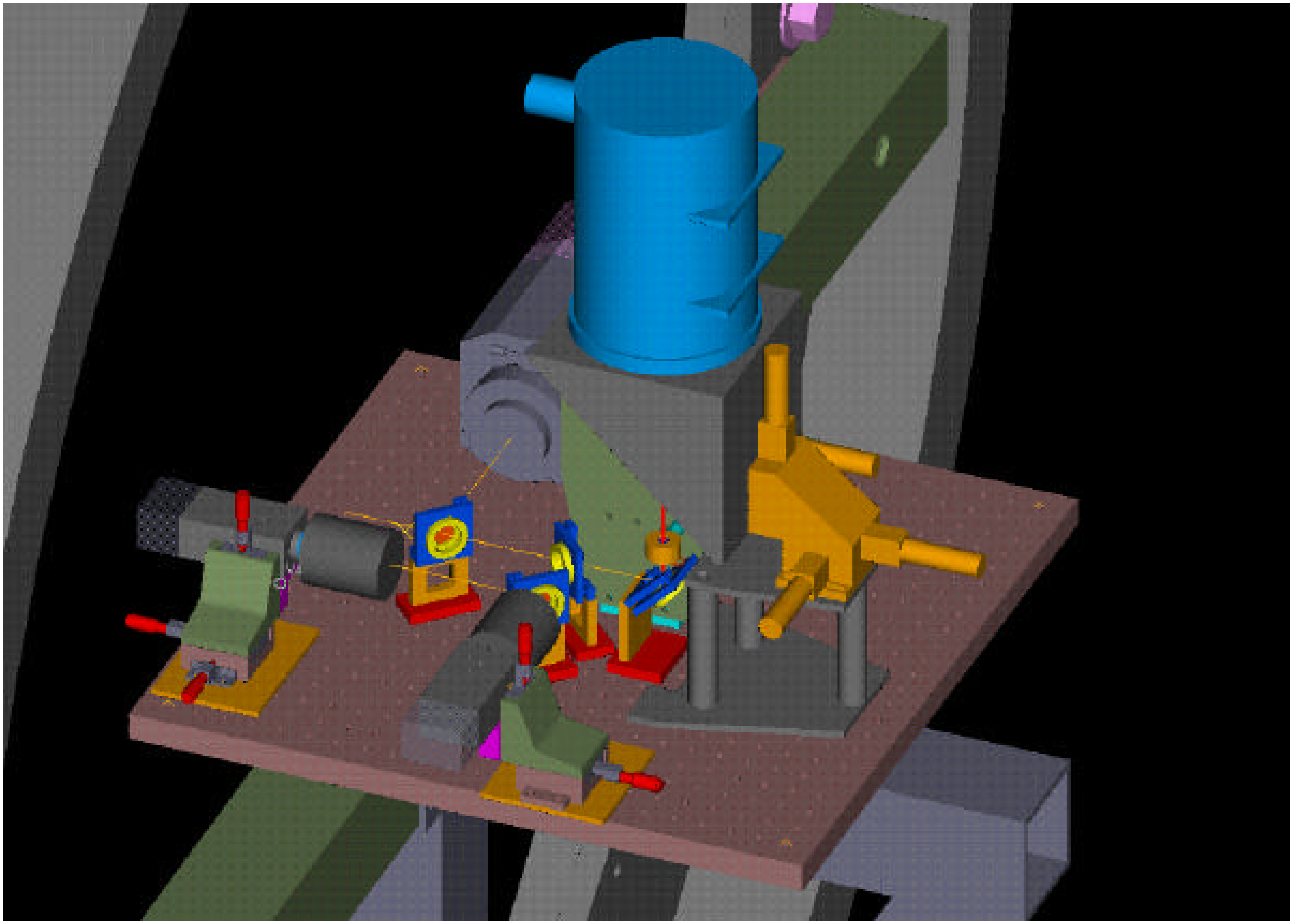


Experiment Layout



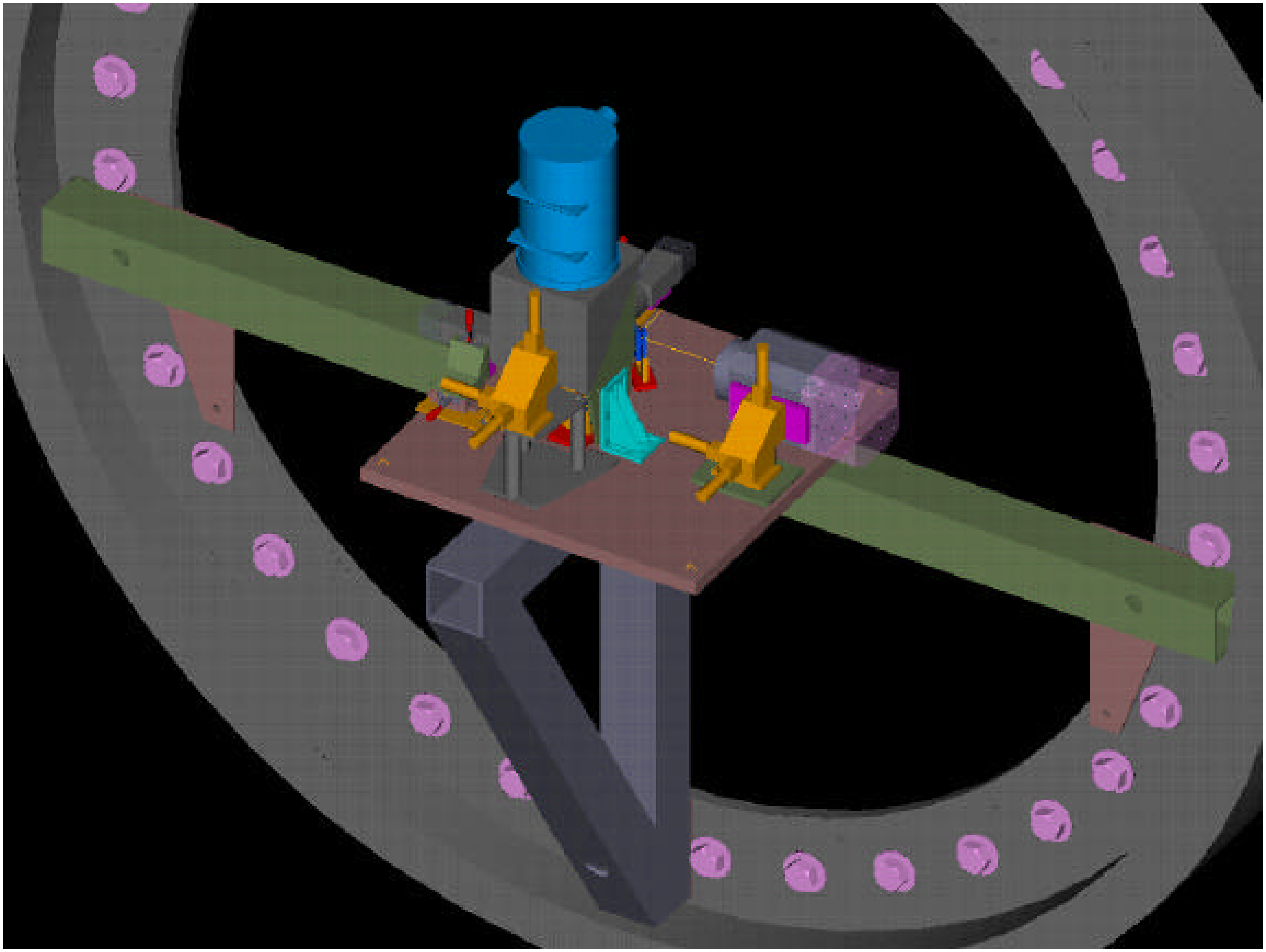
Top View

Experiment Layout



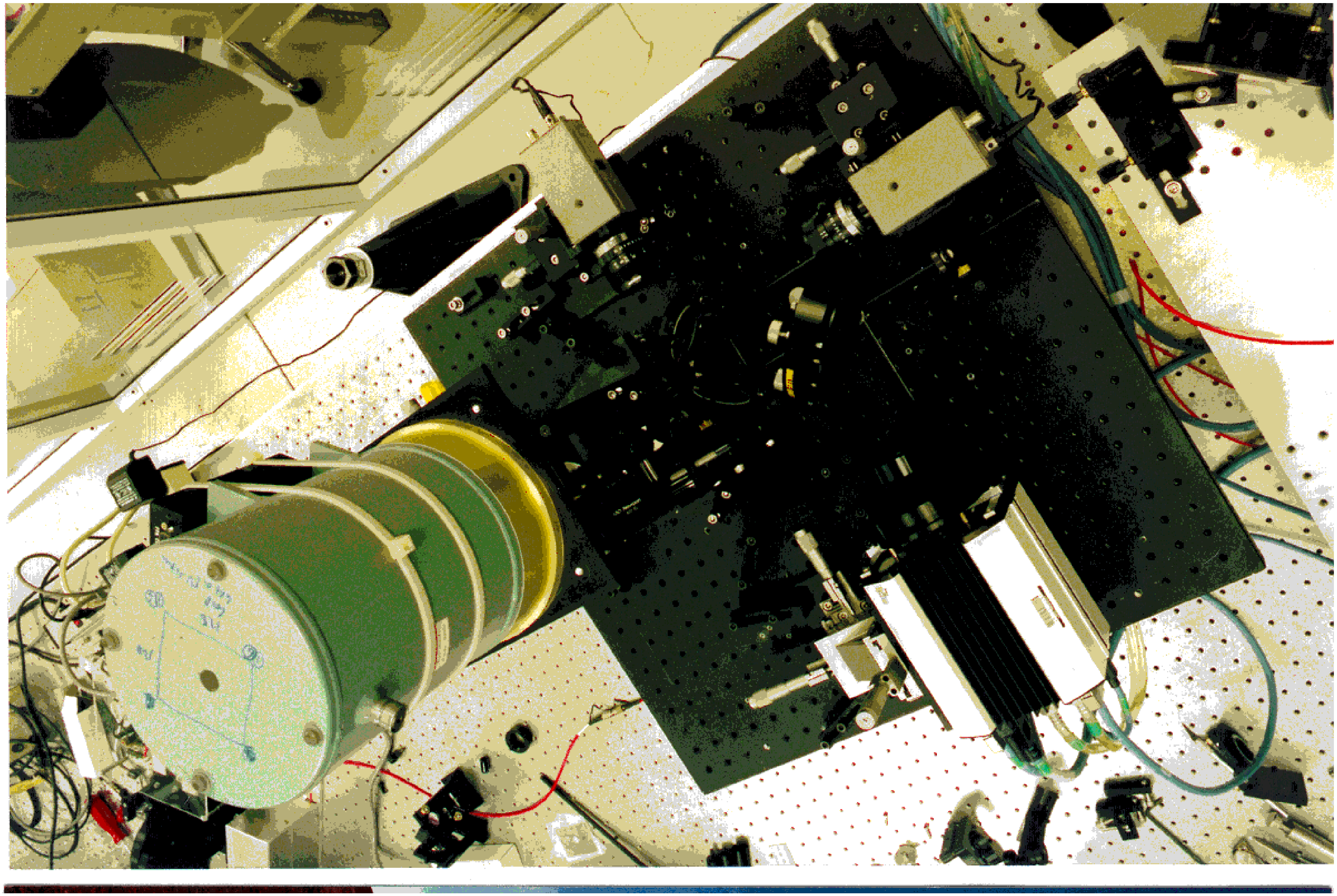
Top-Side View

Breadboard Mounting to Left Nasmyth Platform of Keck II



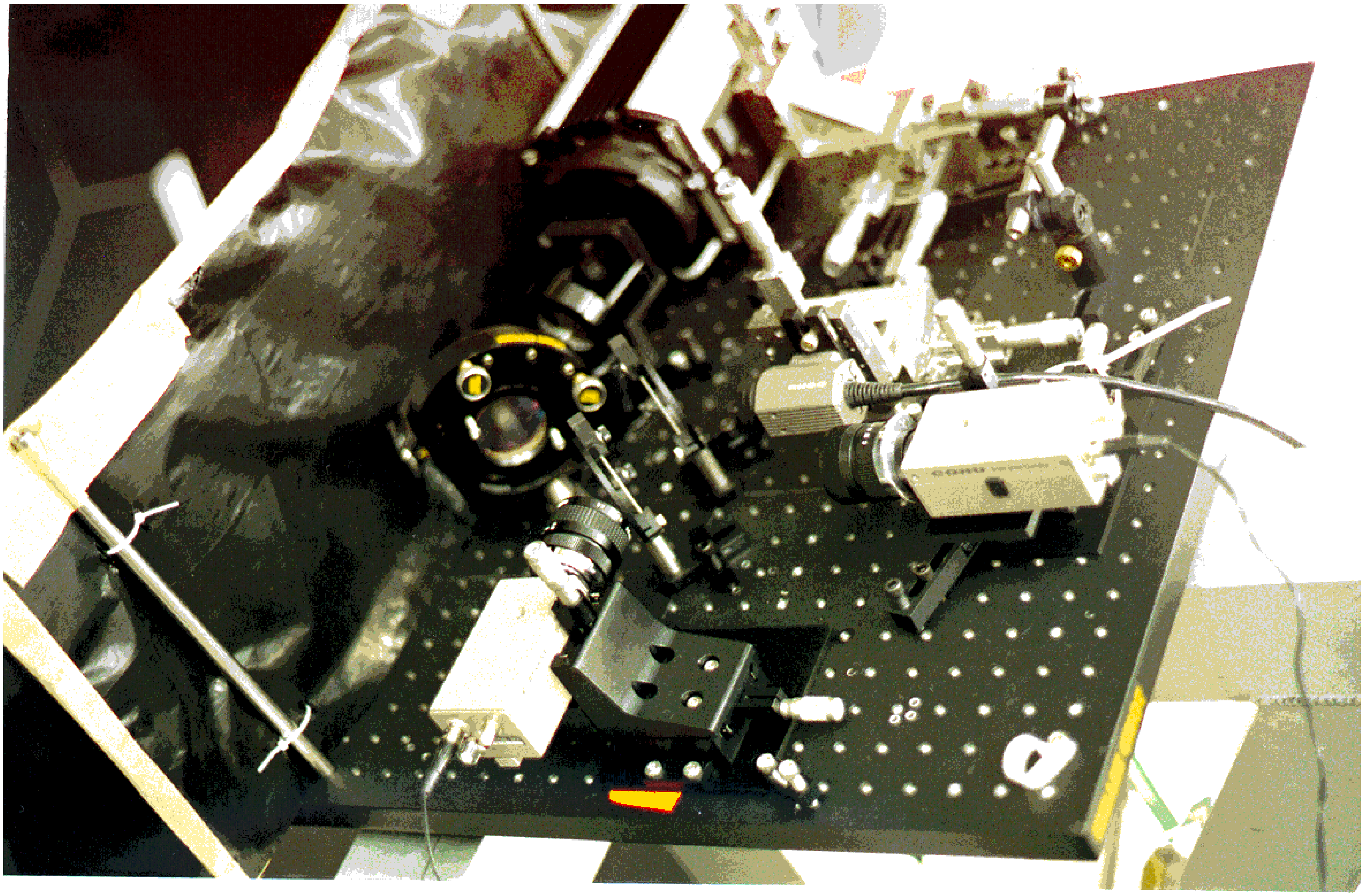
Top-Side View

Photo: Optical Breadboard



Top View

Photo: Optical Breadboard



Top Side View

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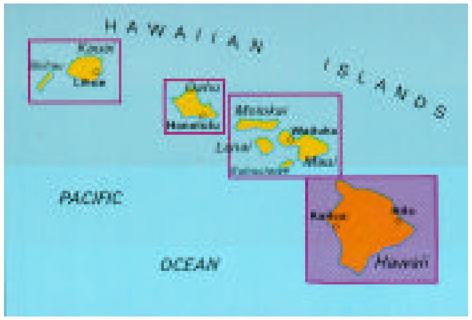
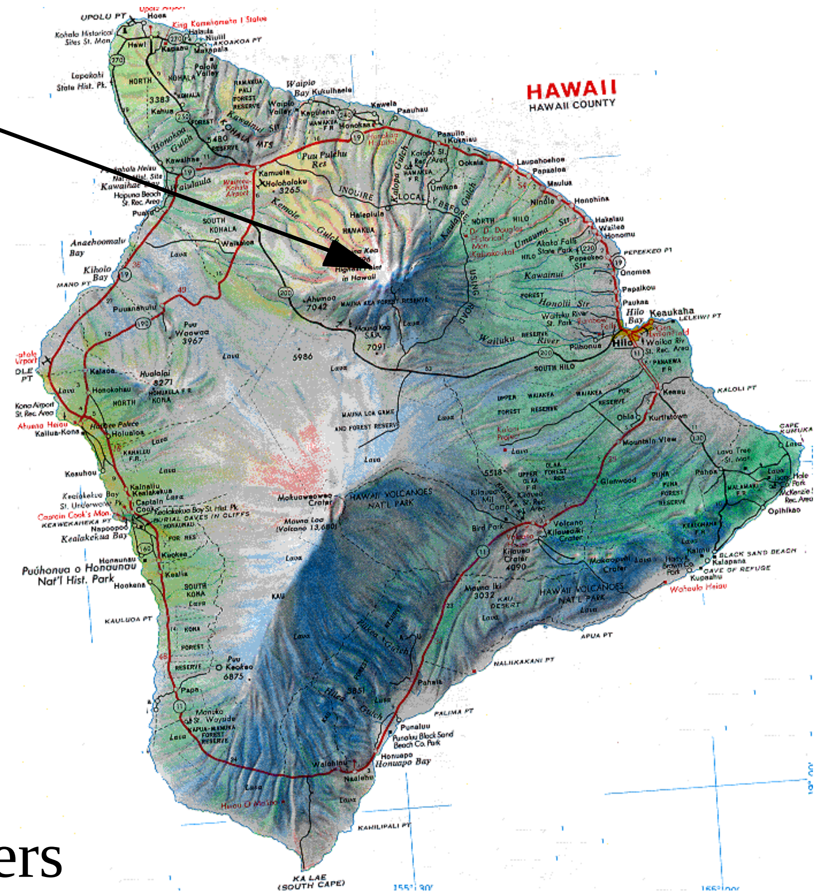
Keck Telescope: Location and Specifications



Keck



Telescope Specifications:

Primary Mirror Diameter = 10 meters
Primary Mirror Focal Length = 17.5 meters
Nasmyth Focus: F/# = 15, f = 149.6 m, Field Diameter = 20 arcmin

Primary Mirror is composed of 36 Hexagonal Segments
Segments: Zerodur, 1.8 m diameter, 75 mm thick, Weight = 880 lbs

Photo: Keck Telescopes

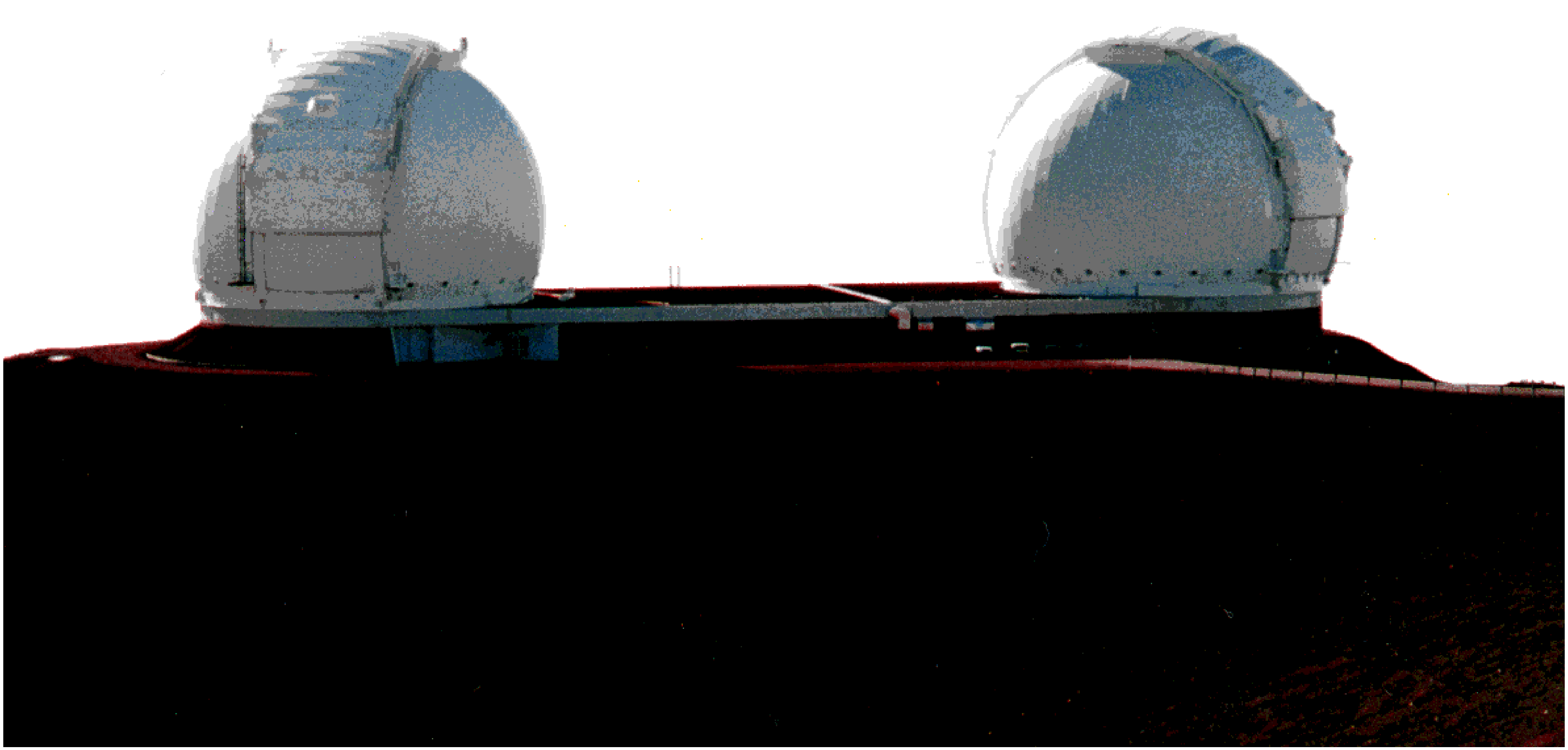


Photo: Keck Dome

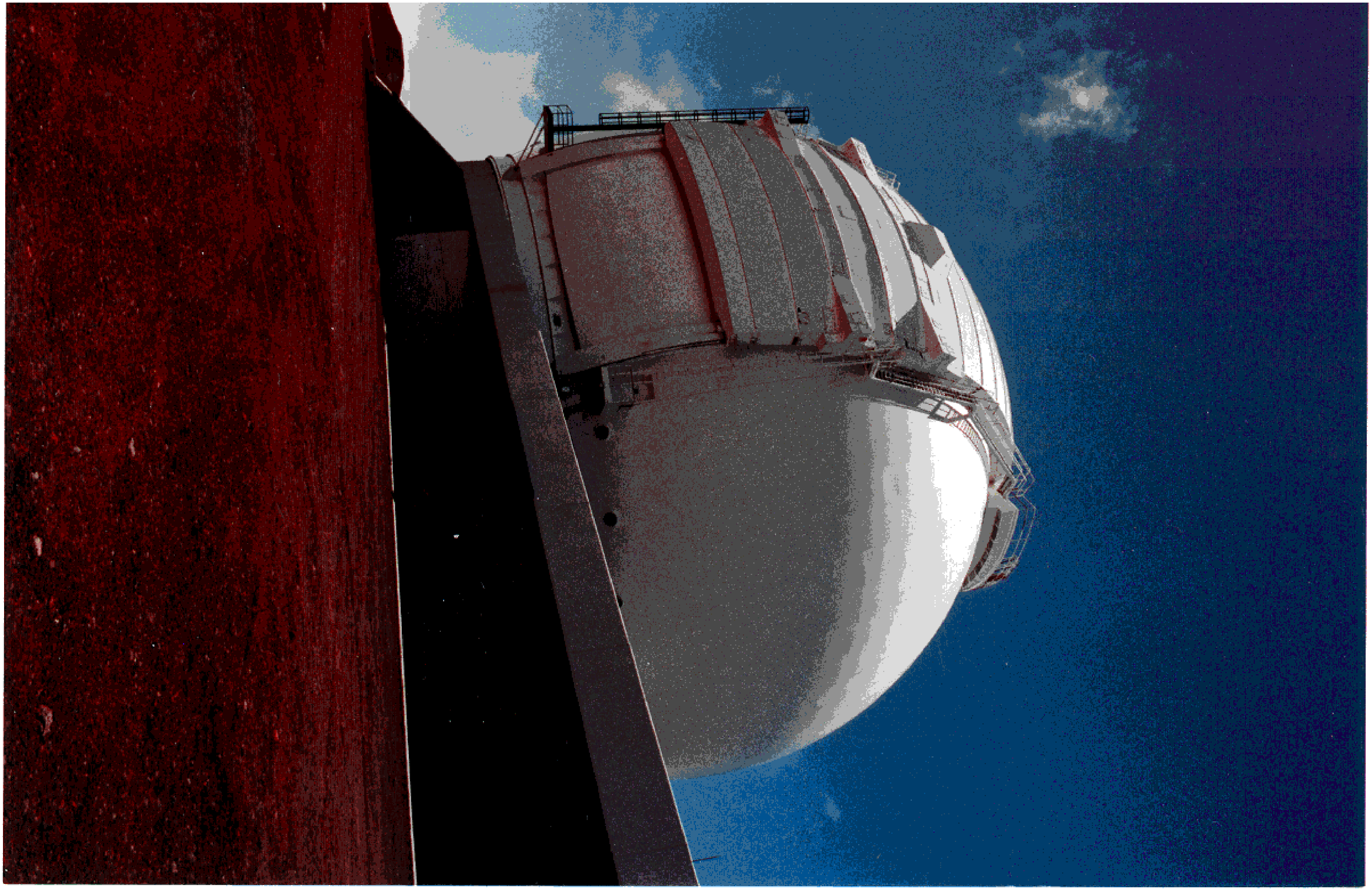


Photo: Keck Model

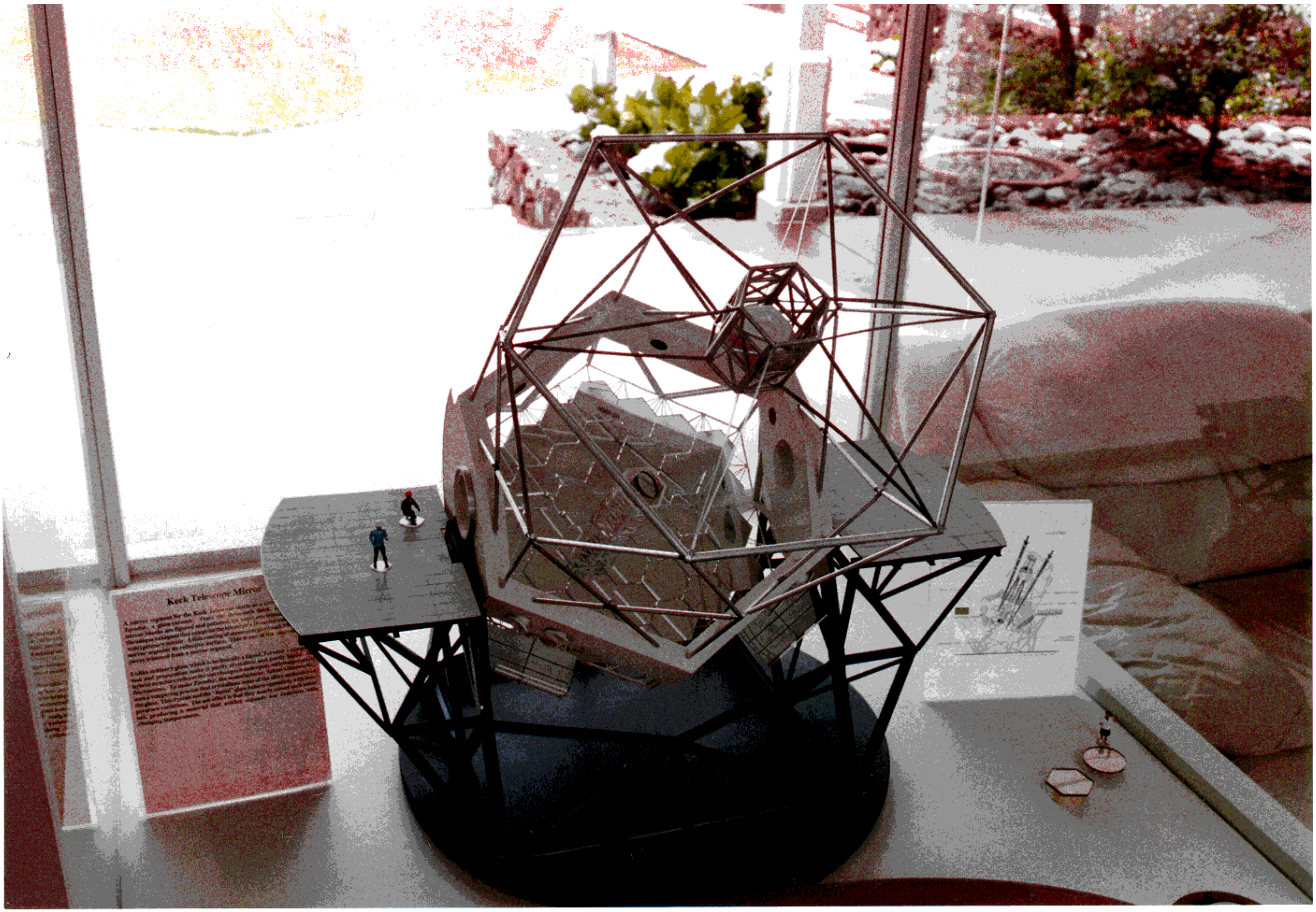
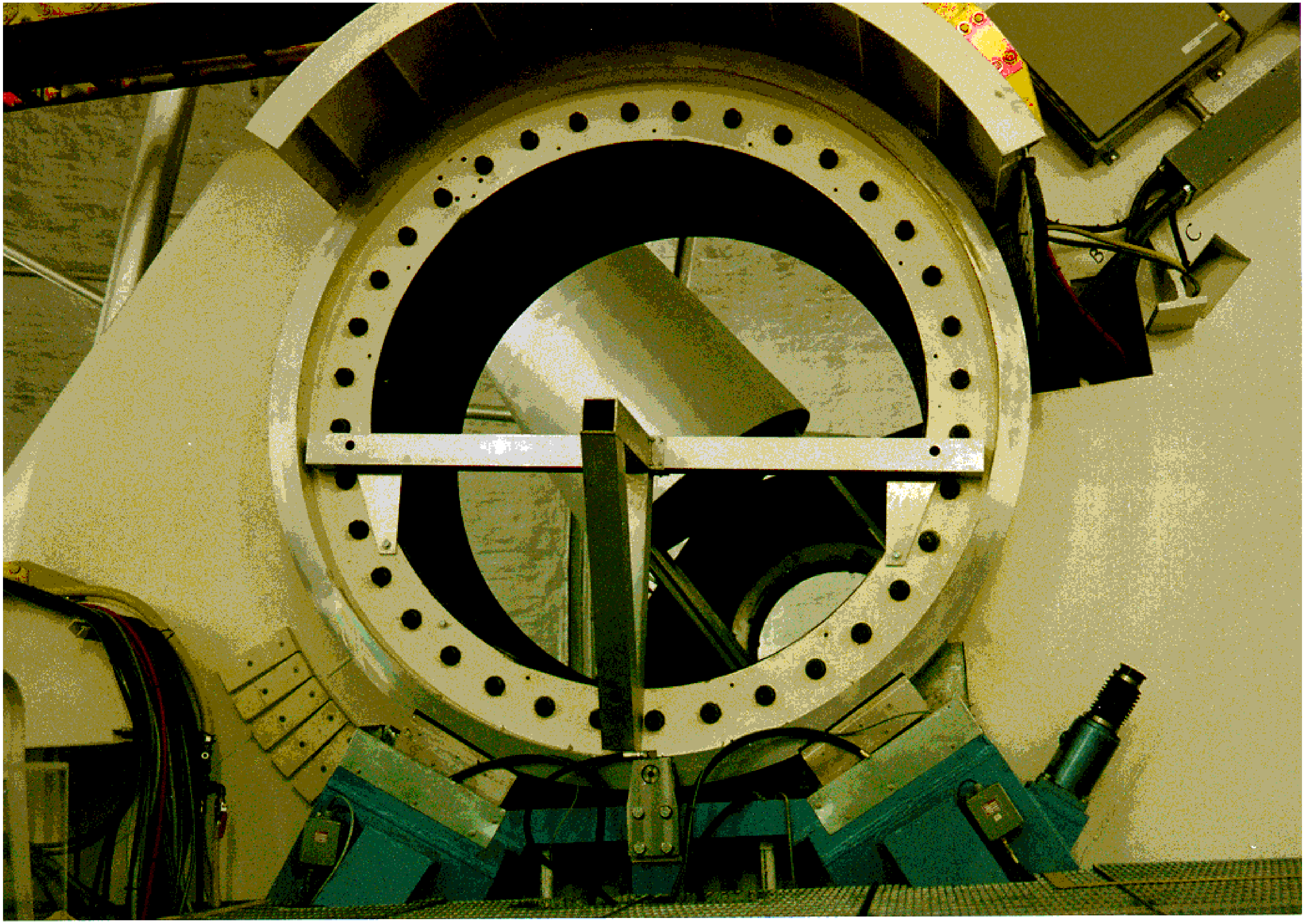


Photo: Experiment Support Structure



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Experiment on Support Structure on Left Nasmyth Platform of Keck II

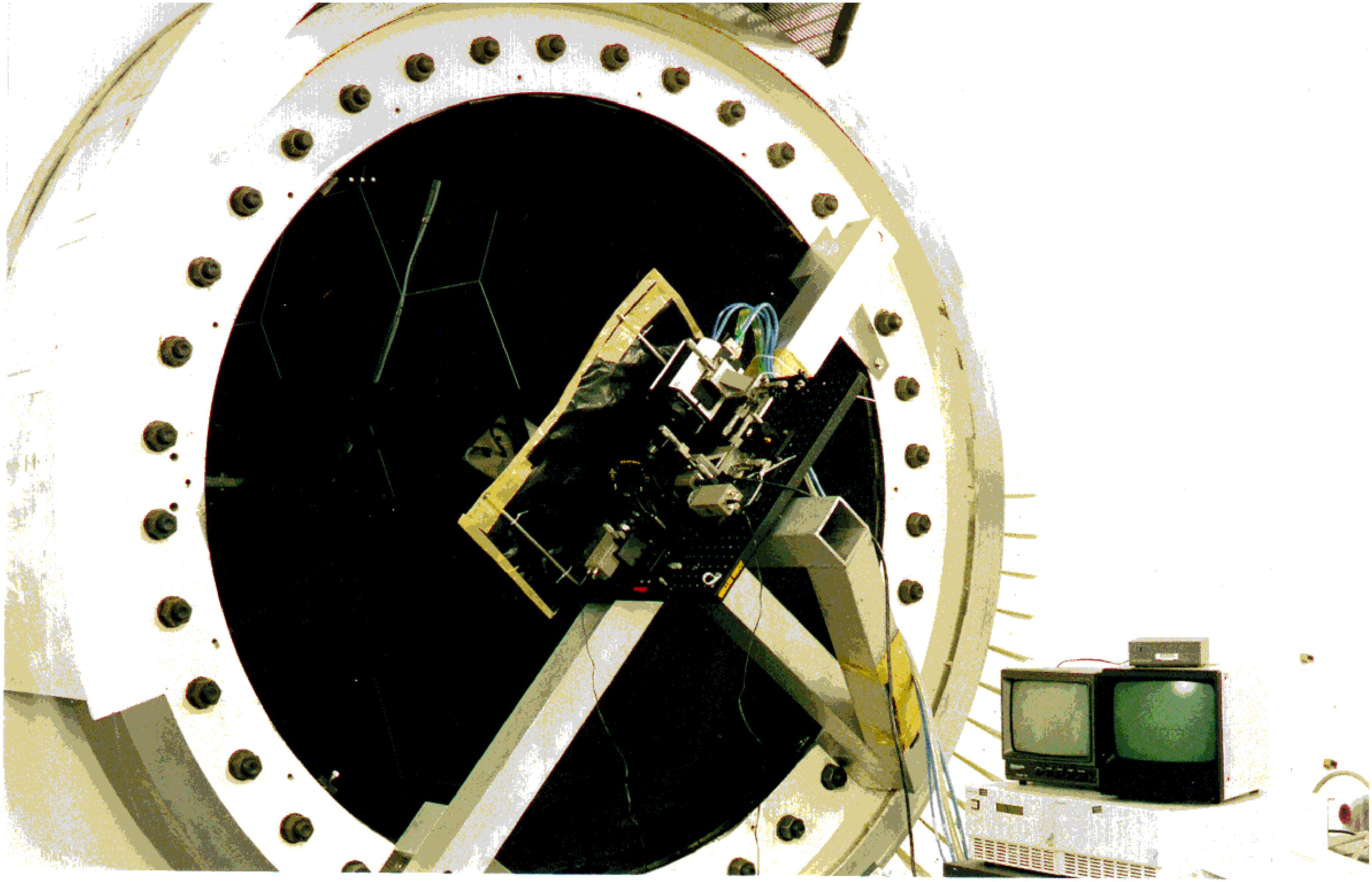

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Photo: Optical Breadboard - Top View

Photo: Optical Breadboard - Top Side View

Photo: Keck Telescopes

Photo: Keck Dome

Photo: Keck Model

Photo: Experiment Support Structure

Experiment on Support Structure on Left Nasmyth Platform of Keck II